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Final report on the Research Workshop on
Nonlinear Time Series Analysis and Applications

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1 The purpose of the Workshop was to explore the current state of research and applications in Nonlinear Time Series Analysis and to explore the common ground between the statistical and mathematical dynamical approach to Nonlinear Temporal Systems. Attention was to be given to the practical use of theoretical developments in this topic. Local arrangements were undertaken by Messrs P R Fisk and M J Prentice, and the academic programme was organised by Professor H Tong.

2 The Workshop was held at the University of Edinburgh between 12th and 25th July 1989, the last two days of which were an "Open Forum" open to interested persons who could attend at their own expense.

3 Dr C M Bowden of the Research Directorate, US Army Missile Command, Redstone Arsenal, Alabama, attended the workshop under the terms of the contract. It is expected that he will make a report on the value of the workshop to him.

4 Oral and written comments from participants indicate that the workshop was regarded as being very successful. Many promising lines of research were identified and a fruitful collaborative dialogue was begun between the mathematical dynamicists involved in applications of chaos theory and statistical specialists in non-linear time series. Dr McKenzie of Strathclyde University is currently spending 10 months with Professor P.A.W Lewis at the Naval Postgraduate School, Monterey, taking further ideas on modelling that originated at the workshop. Similar collaborations among other workshop participants are planned.

5 The Open Forum complemented the closed part of the Workshop by giving an opportunity for others to hear about topics discussed at the Workshop, and to make their own contributions.

6 *Summary of Academic Proceedings*

Lists of those attending the Workshop, and programmes for both the Workshop and the Open Forum, are attached. Abstracts of the talks given are being prepared and will be circulated to participants. Copies of these abstracts will be made available on request.

The Workshop had three main aspects:

- (1) Probabilistic aspects,
- (2) Statistical aspects,
- (3) Dynamical systems.

Within these three a number of applications were described. These included

Econometrics - Granger, Harvey, Terasvirta	Ship dynamics - Ozaki
Hydrology - Jones, Gudmunsson, Tong, Ozaki	Control systems - Lai
Storms - Tawn	Fish population - Gudmunsson
Brain - Babloyantz	Ocean Core - Tunnicliffe-Wilson
Oceanography - Lewis	Football matches - Harvey

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7 Probabilistic Aspects

A number of issues were dealt with under this heading all concerned with the theoretical properties of non-linear time series models. The topics covered can be summarised as follows:

7.1 Ergodicity, stationarity, invertability

Discussion here centred around the problems inherent in modeling non-linear time series. Conditions for ergodicity and stationarity were examined for a simple first-order model which generalized the first-order autoregressive linear model. The concept of a Lyapunov function was used to derive the conditions under which the stochastic series is ergodic. Other approaches used extensions of measures of stability in a simple first-order deterministic model to determine the properties of a stochastically disturbed form of the same model. A related question is whether the stochastic term in a non-linear model can be represented as a function of the present and past members of the observable series. This was examined for the general bilinear model and for threshold autoregressive and moving average/autoregressive models.

7.2 Other issues

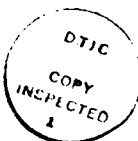
Particular attention was given to non-linear models of sequences of dependent random variables with specified marginals and covariance structure. A model for long-term dependence in non-linear time series was suggested based on a time deformation of a series with short term dependence. Various approaches to M-step non-linear prediction were considered and the problems of time reversability and directionality were examined.

8 Statistical Aspects

These dealt largely with exploratory data techniques for the gaining of an understanding of a non-linear time series, with formal tests for non-linearity, with methods of estimation and identification of non-linear time series models, with diagnostics for the examination of assumptions in non-linear time series models and with the use that could be made of a variety of computer software.

9 Dynamical Systems

Interaction between the four dynamicists and the statisticians at the workshop proved to be the most exciting aspect of the whole meeting. Sparrow and Casdagli introduced the statisticians to concepts in chaos theory such as Lyapunov exponents, correlation dimension, Kolmogorov entropy, folding and stretching, sensitivity to initial conditions, attractors and strange attractors, embedding dimensions among many others. Farmer appraised the role of chaos in statistics and the relevance of statistics in chaos studies. The statisticians responded by suggesting plausible arguments that could lead to a possibly dramatic improvement of the formula for data requirement in the calculation of the dimension of an attractor. A number of statistical problems were identified, solutions of which could have important consequences for the future development of chaos studies. These included: the estimation of the embedding dimension, and/or sampling properties of the correlation dimension, the definition and estimation of the Lyapunov exponents for noisy systems.



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10 *Summary of achievements*

- (1) The most positive contribution was the interaction between the dynamicists and the statisticians. Problems identified as tough but important by one group were identified just the same by the other. This common experience has encouraged closer co-operation across subjects. It is expected that statisticians will begin to make a contribution to research on chaos and be welcomed by the dynamicists. The workshop will be remembered as playing a catalytic role in this.
- (2) In the past, non-linear time series analysis has been confined to specific models. The workshop has broadened the horizon and shown the need, and the way, to focus more intensely on group properties. More attention will have to be paid to the general properties of ergodicity, directionality, long memory, self similarity, non parametric methods, model discrimination, non-regular statistical problems and extremes among many others.
- (3) A number of issues were identified for future resolution in further research. These included: parametric vs nonparametric methods; univariate vs multivariate models; large vs small data sets; single vs multiple realizations; substantive vs empirical modelling; Bayesian vs non-Bayesian approaches. These issues, together with the substantial collection of open problems identified at the workshop, will provide a source of research projects for many years to come.

P R Fisk
28 September 1989

Research Workshop on
Non-Linear Time Series Analysis

Participants

Dr A Bablyoantz	ULB, Bruxelles
Dr M Casdagli	Queen Mary College, London
Professor S K Chan	University of Chicago
Dr W K Li	University of Hong Kong
Dr Z G Chen	Universitat Heidelberg
Sir David Cox	Nuffield College, Oxford
Dr D N Davies	Trent Polytechnic
Dr D Farmer	Los Alamos National Lab
Dr R J Gerrard	The City University, London
Professor C W J Granger	University of California
Professor D Guegan	University Paris XIII
Professor A Harvey	London School of Economics
Dr D A Jones	Institute of Hydrology
Professor T L Lai	Stanford University
Dr J A Lane	University College Wales, Aberystwyth
Professor A J Lawrance	Birmingham University
Professor P A W Lewis	Naval Postgraduate School, Monterey
Dr G Gudmundsson	Central Bank of Iceland
Professor J Liu	University of British Columbia
Dr E McKenzie	University of Strathclyde
Dr T Ozaki	Institute of Statistical Mathematics, Tokyo
Professor J D Petrucci	WPI
Professor P M Robinson	London School of Economics
Professor M Rosenblatt	University of California
Professor R L Smith	Univerisy of Surrey
Dr C Sparrow	King's College, Cambridge
Dr J Tawn	University of Sheffield
Dr T Terasvirta	ETLA, Finland
Professor D Tjøstheim	University of Bergen
Professor H Tong	University of Kent
Professor R S Tsay	Carnegie Mellon University
Dr P D Tuan	Laboratoire TIM3, France
Dr G Tunnicliffe-Wilson	Lancaster University
Dr M West	Duke University

Workshop on Non-linear Time Series Analysis and Applications

Programme

Tuesday 11 July 1989

Introductory meeting

Wednesday 12 July

9.00 - 10.30	H Tong (University of Kent)	Non-linear time series: a dynamical systems approach
11.00 - 12.20	C W J Granger (University of California, La Jolla)	Tests of nonlinearity
1.50 - 2.40	T Terasvirta, (Research Institute of the Finnish Economy, Helsinki)	Testing linearity of economic time series against cyclical asymmetry
2.40 - 3.45	R S Tsay (Carnegie-Mellon University)	Non-linear time series analysis
4.10 - 4.45	J D Petrucci (Worcester Polytechnic Institute, Massachusetts)	A recap of testing non-linearity in time series
7.30 - 9.00	Discussion meeting on general aspects of modelling	

Thursday 13 July

8.50 - 10.10	M Rosenblatt (University of California, La Jolla)	Old unsolved problems
11.00 - 12.00	K S Chan (University of Chicago)	Stability and ergodicity: problems motivated from probability
1.50 - 2.55	A J Lawrance (University of Birmingham)	Directionality and reversability in time series
2.55 - 3.40	D A Jones (Institute of Hydrology)	Towards designer forecasts
4.10 - 4.45	Dr R Cox (Nuffield College, Oxford)	A commentary on matters discussed
7.30 - 9.15	Discussion meeting on numerical calculations of marginal distributions and of particular bilinear models via Chapman-Kolmogorov relation.	

Friday 14 July

8.55 - 10.05	P A W Lewis (Naval Postgraduate School, Monterey)	An exploratory analysis of daily sea surface temperatures and related time series along the California coast
10.05 - 11.05	P M Robinson (London School of Economics)	Non-Gaussian (semi-parametric) econometric models
11.30 - 12.30	D Tjøstheim (University of Bergen)	Non-parametric estimation and identification
1.50 - 2.50	C Sparrow (King's College, Cambridge)	Dynamical systems and chaos
2.50 - 3.40	M Casdagli (Queen Mary College, London)	Chaos and time series analysis
4.10 - 5.25	T Ozaki (Institute of Statistical Mathematics, Tokyo)	Continuous time series modelling

Monday 17 July

9.00 - 10.35	T L Lai (Stanford University)	Adaptive prediction and control in non-linear time series models
11.00 - 12.15	R L Smith (University of Surrey)	Long-range dependence and fractional Brownian models
1.30 - 2.45	E McKenzie (Strathclyde University)	Discrete variate time series models
2.45 - 3.40	J Tawn (University of Sheffield)	The role of multivariate extremes in time series
4.00 - 4.50	Z G Chen (University of Heidelberg)	Towards new sketches of hypothesis testing based on a.s. convergence
4.50 - 5.15	W K Li (University of Hong Kong)	Discriminating non-linear time series models using a bootstrapped Cox test

Tuesday 18 July

9.00 - 10.30	Discussion on open problems: classification problems sample path properties long-range memory reversibility special processes	(Chair: D R Cox)
11.00 - 12.40	D Farmer (Los Alamos National Laboratory)	Introduction to chaos
2.00 - 2.50	R J Gerrard (City University)	Noisy chaos: a Markovian approach
2.50 - 3.10	G Gudmundsson (Central Bank of Iceland)	Threshold models of Icelandic rivers
3.35 - 4.15	D Guegan (University of Paris)	Invertibility of bilinear time series models
4.15 - 5.10	D N Davies (Trent Polytechnic)	The application of dynamic linear modelling and associated software to problems of non linear time series
7.30 - 9.45	Discussion meeting on Chaos	

Wednesday 19 July

9.00 - 9.50	D R Cox (Nuffield College, Oxford)	Long-range dependence and non-linear time series
9.50 - 10.10	P D Tuan (Laboratoire TIM3, France)	Strong consistency of the least-squares estimator for a simple non-stationary model
10.30 - 11.30	K S Chan (University of Chicago)	Estimation of threshold models
11.30 - 12.15	A Harvey (London School of Economics)	Computer demonstration of STAMP package (Structural Time Series Analyzer, Modeller and Predictor)
1.50 - 3.05	A Harvey (London School of Economics)	Time series models for count or qualitative observations
3.40 - 4.30	J A Lane (University College, Wales, Aberystwyth)	Approximations for non-linear autoregressive forecasting
4.30 - 5.20	G Tunnicliffe-Wilson (Lancaster University)	Genstat 5 - an application to a time scale problem

Thursday 20 July

9.00 - 10.40	Discussion of open problems posed by Tsay and Lawrence	
11.00 - 12.15	C W J Granger (University of California, La Jolla)	A survey of the interface between econometrics and non-linear time series
1.50 - 2.35	G Gudmundsson (Central Bank of Iceland)	Time series application to fish catch data
2.35 - 3.35	C Sparrow (King's College, Cambridge)	Dimension calculations with reference to the problem of data requirements
4.05 - 5.15	A Babloyantz (Free University of Brussels)	Chaotic time series of electrophysiology
7.30 - 9.00	Discussion meeting on Chaos	

Friday 21 July

9.00 - 10.05	E McKenzie (Strathclyde University)	Minification process
10.30 - 11.05	Z G Chen (University of Heidelberg)	Reversibility of multiple time series
11.05 - 11.45	J Liu (University of British Columbia)	Some results in bilinear and threshold models
11.45 - 12.00	Discussion of hydrological control problem; modelling a reservoir on the river Thames	
1.45 - 3.05	Address by representatives of the SERC Mathematics Committee to British participants	
3.30 - 5.00	Discussion of open problems chaired by R L Smith	

OPEN FORUM
Programme

Monday 24 July

9.00 - 10.30	H Tong (University of Kent)	Recent developments in non-linear time series
11.00 - 12.30	R Tsay (Carnegie-Mellon University)	Some topics in the statistical aspects of non-linear time series
2.15 - 2.45	C Chatfield (University of Bath)	Multiplicative Holt-Winters forecasting: non-linear aspects
2.45 - 3.15	G J Janacek and A L Swift (University of East Anglia)	Experience with a class of non-normal time series
3.45 - 4.15	S Mittnik (State University of New York)	Estimation of general non-linear dynamic time series

Tuesday 25 July

9.00 - 10.30	A Babloyantz (Free University of Brussels)	Chaotic time series
11.00 - 12.30	R Gerrard (City University)	Some topics in the probabilistic aspects of non-linear time analysis
2.15 - 3.30	Demonstrations of computer software	